Hyperspectral Remote Sensing of the Coastal Ocean: Adaptive Sampling and Forecasting of *In situ* Optical Properties

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LONG-TERM GOAL

We are developing an integrated rapid environmental assessment capability that will be used to feed an ocean nowcast/forecast system. The goal is to develop a capacity for predicting the dynamics in inherent optical properties in coastal waters. This is being accomplished by developing an integrated observation system that is being coupled to a data assimilative hydrodynamic bio-optical ecosystem model. The system was used adaptively to develop hyperspectral remote sensing techniques in optically complex nearshore coastal waters.

OBJECTIVES

Our objectives were to 1) develop and deploy moored, shipboard, and autonomous bio-optical systems in the coastal ocean to ground-truth remote sensing imagery, 2) use rapid environmental assessment techniques to quantify the physical, chemical and biological processes that define the spatial and temporal variability in the spectral IOPs for the nearshore coastal ocean during summer-time upwelling, 3) refine and calibrate existing hyperspectral optical models to derive IOPs from remotely sensed data using the above datasets and, 4) in collaboration with other principal investigators couple a radiative transfer ecosystem module to the data-assimilative hydrodynamic model. Our analysis on inverting signatures to bulk *in situ* IOP constituents, use derived phytoplankton signatures as inputs to

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14. ABSTRACT
We are developing an integrated rapid environmental assessment capability that will be used to feed an ocean nowcast/forecast system. The goal is to develop a capacity for predicting the dynamics in inherent optical properties in coastal waters. This is being accomplished by developing an integrated observation system that is being coupled to a data assimilative hydrodynamic bio-optical ecosystem model. The system was used adaptively to develop hyperspectral remote sensing techniques in optically complex nearshore coastal waters.

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bio-optical productivity models, define how the inherent optical properties impact both operational horizons of emergent light fluxes and remote sensing reflectance measured by the international constellation of satellites and aircraft. Finally we are conducting hindcast studies with coupled optical/physical numerical model.

APPROACH

We have conducted a series of Coastal Predictive Skill Experiments (CPSE) at the Long-term Ecosystem Observatory (LEO-15) in order to understand the physical forcing of the nearshore optical properties. To this end, coordinated shipboard (physical and bio-optical) and AUV adaptive sampling surveys of the upwelling centers were conducted based on the real-time remote observations and the model forecasts. The observational capability is used then to characterize and model the variability in the physics and the associated in-water optical properties in order to ground-truth hyperspectral imagery collected by COIS sensors mounted on aircraft.

WORK COMPLETED

The field-work is accomplished at LEO-15, however we are pursuing similar efforts for calibration of aircraft and *in situ* hyperspectral sensors off California in October, 2002. The LEO-15 experiments were focused around dynamical forecasts generated through the Regional Ocean Model (ROMs) forecasts. These forecasts robustly predicted alternating upwelling/downwelling events. These forecasts, real-time CODAR fields, and *in situ* data from the autonomonous nodes assisted in choosing flight missions for the aircraft (PHILLs 1, PHILLs 2, AVIRIS, Proteus, SPECTIR) and position three ships under the aircraft for *in situ* validation. Furthermore the *in situ* nodes were outfitted to measure a full suite of inherent optical properties. Shipes were similarly outfitted. Field sampling was coordinated through the modeling/observation system and allowed for 1) 16 clean overflights providing hyperspectral ocean color data with complete remote sensing ground truth data from the research fleet, 2) 5 days with more then two aircraft flying at one time allowing for unique vicarious calibration between aircraft systems, and 3) calibration of atmospheric parameters using NASA-funded aircraft. During the three years of field work in excess 700 discrete samples were collected and have been analyzed in the lab for filter pad absorption spectra, particle size, phytoplankton pigmentation, and organic carbon/nitrogen content.

The ROMS systems were coupled to the EcoSim model. This required substantial modification of the EcoSim model, which was not written in to run in parallel. ROMS is a free-surface, hydrostatic, primitive equation model initially based on the s-coordinate Rutgers University Model (SCRUM) described by (Song et al., 1994). ROMS was rewritten by the UCLA and Rutgers ocean modeling groups to improve its numerics and efficiency in single and multi-threaded computer architectures. New features include high-order advection schemes; accurate pressure gradient algorithms; several subgrid-scale parameterizations; atmospheric, oceanic, and benthic boundary layers; radiation boundary conditions; and data assimilation. EcoSim, which is upper ocean ecological model, was successfully coupled to the ROMS model and the shared memory parallel version (using OpenMP) of the ROMS/EcoSim code that we used to produce forecasts on the New Jersey coast for ONR's COMOP/HyCODE program (Arango et al., 2002) in July 2001 required 25 hours of wall clock time to process a 31 day simulation of a 100 x 240 (horizontal) x 25 (vertical) grid when executing on 16 (out of 256) processors of the NRL Origin3800 supercomputer (neo.cmf.nrl.navy.mil). Additionally, Ecolight, a version of the Hydrolight 4.1 radiative transfer model,was added to the ROMS/EcoSim modeleing system. The advantage of adding Ecolight is that it provides an accurate solution of the

RTE for any water body, given the absorption and scattering properties of the water body, the incident sky radiance, and the bottom reflectance (for finite-depth waters) but is runs one thousand times faster than the standard version of Hydrolight.

RESULTS

FIELD DATA During the experiment we experienced a wide gradient of hydrographic conditions, which provided a wide dynamic range ideal for calibrating the aircraft hyperspectral sensors. The adaptive sampling strategy allowed us to optimize this calibration exercise, with over 10 days of high quality *in situ* and aircraft data. Currently personnel FERI, NRL-Stennis, Rutgers and Cal Poly State University have been comparing the *in situ* and aircraft optical data. The conditions that dominated the optical signals varied between the two years. Summer 2000 was dominated by a large plume of Hudson River water. In contrast alternating upwelling and downwelling events dominated summer 2001.

Inversion of in situ data and optical tagging of water masses: We developed a method that takes ac-9 data and inverts the bulk signal into its constituent end members. The inversion method estimates the coefficients (w_i) and exponential slopes (*s, r*) using a non-linear constrained least-squares regression. Derived particulate, detrital and phytoplankton loads were compared to independent in situ and discrete data. Good agreement was achieved between measured and modeled particulate and phytoplankton spectra. Therefore the derived particulate spectra could be quantitatively derived from the ac-9 with no major bias as a function of wavelength. Comparing to HPLC data the inverter could predict ($p<0.05$) the concentration of chlorophyll c and phycobilin-containing phytoplankton. We compared the water masses delineated optically from these derived products to those predicted with temperature and salinity in an effort to extending classical T-S water mass analysis into multi-dimensional space using derived optical parameters that ultimately could derived using remote sensing platforms (aircraft or satellites). The T-S relationships detected the presence of significantly different water masses within and between each year, however their boundaries were difficult to resolve from T-S structure alone. While these optical parameters are semi-conservative, the relative change of these parameters is longer than many coastal ocean processes enhancing their potential utility. Examples of feature that were easy to determine from HyCODE include the Hudson River plume with the high concentration of large particles, phytoplankton, CDOM and detritus during summer 2000. Here the river was dominated with shallow CDOM slopes consistent with terrestrially derived materials. A second example was dense bottom water, which was easily identified optically by steep CDOM slopes. The water mass clusters for the temperature/salinity and the optics (CDOM slope & load, detritus slope and load, and phytoplankton load) generally agreed with each delineating 3 major water masses in summer 2000 and 2 major water masses in 2001.

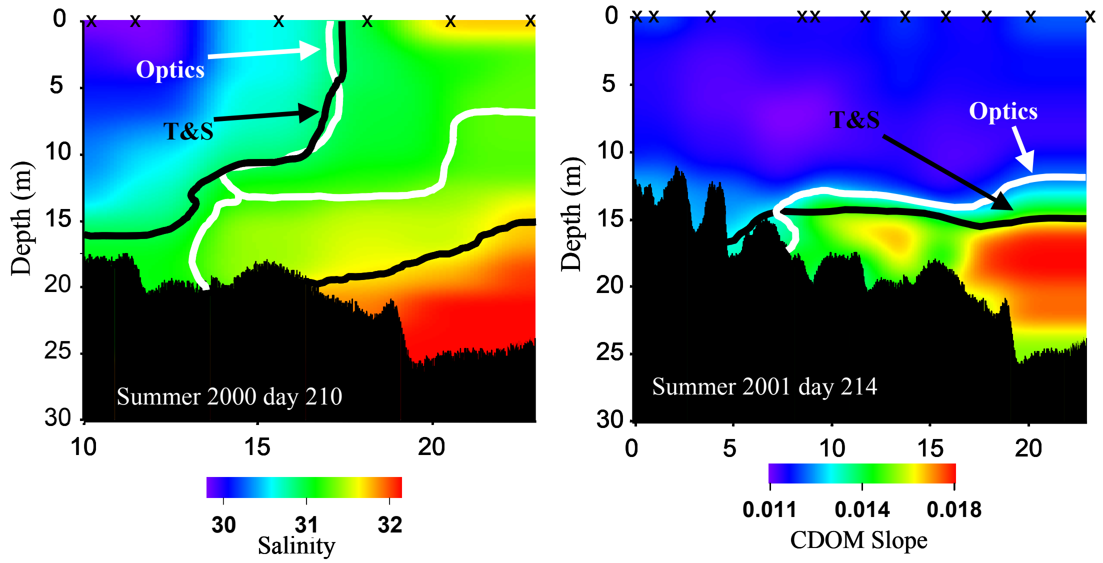

Figure. 1. Cross-shore transects from a day in Summer 2000 and 2001. The black lines represent the water mass classification based upon the entire summers temperature and salinity data. The white line represents the water masses identified based on the ac-9 inverter for the entire summers dataset. The water masses were calculated from the different parameters by subtracting the mean of the data set and dividing by the standard deviation of the data set. Based on Euclidian distance, a distance matrix was calculated for the data set, and then hierarchically clustered according to Ward's linkage (Ward 1963). The generated similarity index was used in conjunction with a multivariate analysis of variance to define the major water masses.

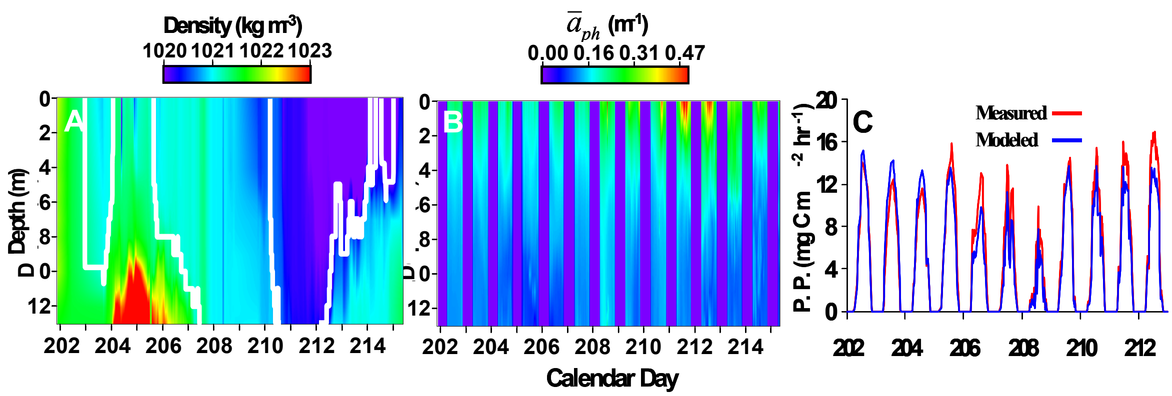

Figure 2: Density profiles during summer 2000. (A) Water mass analysis suggests three major water masses defined as white lines; deep intrusion layer, intermediate water and Hudson River Plume. (B) Spectrally-weighted absorption was computed by combining modeled spectral scalar irradiance from Hydrolight and the absorption of phytoplankton computed from the OSI. Using the desired absorption in a bio-optical model, (C) modeled photosynthesis compared well to measured values using ^{14}C incubations.

Bio-optical models for primary productivity. For summer 2000 we used the optical profiling node to collect time series. Using the ac-9 inversion method the spectral absorption of phytoplankton. The bulk absorption, attenuation and backscatter data from the optical profiler were used as input into a radiative transfer model (Hydrolight v. 4.2) to model the spectral scalar irradiance from 400-700 nm. These spectral were combined with the modeled phytoplankton absorption spectra from the OSI model to compute the spectrally-weighted absorption coefficient ($\overline{a}_{ph}$). The estimates of $\overline{a}_{ph}$ were used as input to compute primary productivity. Modeled integrated water column productivity were within 11% of measured productivity results using ^{14}C incubations.

IMPACT/APPLICATIONS

An integrated system for predicting the 3-dimensional structure of coastal currents, water density and in-water optical properties on the time scales of days is essential to numerous naval operations such as mine counter measures, special forces operations, amphibious landings, and shallow water anti-submarine warfare. The NEMO system is being designed to provide hyperspectral ocean color data for mapping in-water constituents in areas of high naval interest and the derived algorithms. Finally hydrodynamic/optical forecasting system provides the key to integrate and forecast the observed optical properties over time. HyCODE has played a central role to developing optical REMUS AUV and optical Webb Glider. All these observation and modeling systems are relocatable and will be key for future naval operations and homeland defense.

TRANSITIONS

The data is being freely shared. Data will be disseminated to the ONR WOOD database. Data that is just being finished processed will burned to data CD's and is available via one-way FTP. Data will be shipped to the WOOD system in October. The optical data is currently being utilized by NRL and NASA remote sensing projects. Finally the ongoing real-time data, for which the HyCODE program was central to for development, continues to be accessed via the web (over 65,000 hits/day) by the general public, Naval METOC groups, NAVO, NOAA Oil Spill response teams, and the U.S. Coast Guard.

RELATED PROJECTS

There were over 27 major institutional partners during the 2000-2001 experiments a large number supported by the HyCODE program. These efforts also complemented other independent efforts such as 1) validatation of NAVAIR's KSS Lidar system, 2) ONR-YIP funded AUV bioluminescence prediction efforts, 3) ONR-STTR sponsored efforts to develop a "smart" fleet of automated Webb Gliders, 4) SeaSpace Inc. efforts to intercalibrate the international constellation of ocean color satellites, 5) calibration and refinement of a suite of NRL-derived satellite algorithms, 6) calibration of atmospheic parameters with NASA's atmospheric Chesapeake Lighthouse and Aircraft Measurements for Satellites experiment, 7) field infrastructure for NASA's NIP and PECASE remote sensing projects, and 8) model development for ONR's CBLAST Program.

PUBLICATIONS RESULTING FROM HYCODE SUPPORT

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